

# QCD, hadrons and beyond

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**Abstract.** I give a summary of Section E of the sixth edition of the Conference *Quark confinement and the hadron spectrum*. Papers were presented on different subjects, from spectroscopy, including pentaquarks and hadron structure, to new physics effects (non commutative field theories, supersymmetry and extra dimensions) and the problem of color confinement, both in ordinary Yang-Mills models and in supersymmetric Yang-Mills.

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## PENTAQUARKS, SPECTROSCOPY AND HADRON STRUCTURE

Starting from January 2003 several experiments have produced evidence for a few baryonic resonances whose simplest interpretation in terms of the quark model is that of a bound state of five quarks, more exactly four quarks and an antiquark. The first observed pentaquark has been the baryonic resonance  $\Theta^+(1540)$ , reported by several experiments: LEPS [1], DIANA [2], CLAS [3, 4], SAPHIR [5], HERMES [6], as well as by analyses of old bubble chamber experiments [7]. Several new experimental results on this state have been presented at this conference, and a lively discussion took place also in Section E. All the experiments giving evidence of  $\Theta^+(1540)$  show that this resonance decays into  $K^+n$  or  $K_s^0 p$  with a width compatible with experimental resolution ( $\Gamma \sim$  a few MeV). The former decay, with strangeness  $S = +1$  and baryonic number  $B = 1$  is exotic. In principle one might model this state as a molecule  $K^+n$ ; this interpretation would require an interplay of an attractive interaction with a range of  $\sim 1$  fermi and the centrifugal barrier ( $\ell \neq 0$ ); however such a model is disfavored since it would produce too large widths. As remarked above, the simplest quark model interpretation is that of a pentaquark, i.e. an exotic state formed by five quarks:  $udud\bar{s}$ . Other narrow exotic cascade states, e.g. a  $\Xi^{--}$  state with quantum numbers  $B = 1, Q = S = -2$ , and also a  $\Xi^-$  and  $\Xi^0$  state have been reported by the NA49 Collaboration, see [8]. Also these signals can be interpreted as pentaquark states, e.g. for  $\Xi^{--}$ ,  $dsds\bar{u}$ .

In the first year there has been an almost continuous flow of experimental results, but, starting from January 2004, new data appeared, many with negative results [9], e.g. BES, OPAL, PHENIX, DELPHI, ALEPH, CDF, BaBar, E690.

Negative results from the Hera-B experiment were presented in Section E by M. Medinnis. The search for  $\Theta^+(1540)$  and  $\Xi^{--}$  in  $pA$  collisions at 920 GeV from this experiment only resulted in upper bounds. More precisely, looking at the  $pK_s^0$  invariant mass, Hera-B finds the upper limit

$$\mathcal{B}d\sigma/dy|_{y=0} = 3.7\mu b/N \quad (1)$$

at 1530 MeV/ $c^2$  and

$$\mathcal{B}d\sigma/dy|_{y=0} = 2.4\mu\text{b}/N \quad (2)$$

at 1540 MeV/ $c^2$ . The upper limit for  $\Xi^{--}$  production is  $2.5\mu\text{b}/N$  at 1862 MeV/ $c^2$ , i.e. in the mass region where NA49 finds positive results.

J. Engelfried reported results on the search of strange and charmed pentaquark states at Selex. This collaboration finds no evidence of the strange pentaquark  $\Theta^+$ , while for the charmed pentaquark  $\Theta_c$  no conclusion can be drawn yet.

The charmed pentaquark state  $\Theta_c^0$  has been searched by the H1 and ZEUS Collaborations at DESY. L. Gladilin reported results from these two experiments. H1 [10] finds a  $5\sigma$  signal in deep inelastic scattering and a signal in photoproduction at the same mass ( $\sim 3.1$  GeV). This narrow anticharmed state is seen through its decays into  $D^{*-}p + c.c.$  and its minimal quark content is  $udud\bar{c}$ . On other hand ZEUS does not find it [11]. As to the strange pentaquark  $\Theta^+$ , ZEUS [12] observes  $221 \pm 48$  events in the channel  $pK_s^0$  with a mass of the  $\Theta^+$  equal to  $1521.5 \pm 1.5$  MeV. On the other hand no signals of the  $\Xi^{--}$  pentaquark is found by this collaboration.

Much experimental effort is expected in the near future to clarify these experimental issues. The origin of the discrepancies might be in the difference of production mechanisms, leading to different yields in different experiments. A careful analysis of the different assumptions in the experimental analyses would be certainly welcome, in particular those related to the kinematical cuts. In any event high statistics experiments should provide an answer in the near future. For the time being we can certainly assert that the appearance of exotic states, coming after years of fruitless experimental researches of exotica, has revived theoretical interest in QCD spectroscopy and its low energy models. Pentaquark states were indeed predicted long ago in the framework of the Chiral Soliton Model [13, 14], which is an extension to three flavors [15, 16, 17] of the Skyrme model [18, 19]. In the Chiral Quark Soliton Model [20, 21] all baryonic states are interpreted as arising from quantizing the chiral nucleon soliton and the pentaquark emerges as the third rotational excitation with states belonging to an antidecuplet with spin  $s = 1/2$ . Other interpretations have been proposed after the first results on  $\Theta^+(1540)$ , most notably the one of Jaffe and Wilczek [22, 23] who propose that the  $\Theta^+$  comprises two highly correlated  $ud$  pairs (diquarks:  $\mathcal{Q}$ ) and an  $\bar{s}$ . Diquarks properties are similar to those of the diquark condensates of QCD in the high density color-flavor-locking (CFL) phase [24]. Both diquarks are in spin 0 state, antisymmetric in color and flavor. Together they produce a  $\mathcal{Q}\mathcal{Q}$  state in the flavor-symmetric  $\mathbf{6}_f$  that must be antisymmetric in color and in  $p$ -wave to satisfy Bose statistics. When combined with the antiquark the diquarks produce a  $\mathbf{\bar{10}}_f$  with spin 1/2 and positive parity (they can also produce a  $\mathbf{8}_f$ , and mixing is possible).

The hypothesis that the attractive interaction in the antisymmetric color channel may play a role both at low and high density quark matter is especially interesting in the light of the quark hadron continuity which has been suggested [25] to exist between the CFL and the hypernuclear phase. Due to the formation of the CFL condensate that breaks color, flavor and the electric charge, though preserving a combination of the electric charge and of the color generator  $T_8$ , the physical states are obtained by dressing the quarks by diquarks. The result is that in this phase eight quarks have exactly the same quantum numbers of baryons. Also the ninth quark corresponds to a singlet with a gap

which is twice the gap of the octet. The same phenomenon takes place for the other states. For instance, the gluons are dressed by a pair  $\overline{Q}Q$  giving rise to vector states with the same quantum number of the octet of vector resonances ( $\rho$ , etc.).

Quark-hadron-continuity plays a role in relating quark and baryons in the low-lying octet. Apparently it also matters in assigning a role to diquark attraction at zero baryonic densities. In a recent paper [26] it has been suggested that another sign of it is the existence of baryon chiral solitons also at finite density. The mechanism of its formation is based on the existence of condensates giving rise to color superconductivity and Nambu Goldstone Bosons (NGB) associated to the breaking of global symmetries. One starts with the effective lagrangian for the Nambu-Goldstone bosons written in terms of the fields bosonic fields  $X$  and  $Y$  associated to the right handed and left handed spin 0 condensates [26]:

$$\begin{aligned}\mathcal{L} = & -\frac{F_T^2}{4}\text{Tr}\left[\left(X\partial_0X^\dagger - Y\partial_0Y^\dagger\right)^2\right] - \alpha_T\frac{F_T^2}{4}\text{Tr}\left[\left(X\partial_0X^\dagger + Y\partial_0Y^\dagger + 2g_0\right)^2\right] \\ & + \frac{F_S^2}{4}\text{Tr}\left[\left|X\nabla X^\dagger - Y\nabla Y^\dagger\right|^2\right] + \alpha_S\frac{F_S^2}{4}\text{Tr}\left[\left|X\nabla X^\dagger + Y\nabla Y^\dagger + 2\mathbf{g}\right|^2\right] \\ & + \frac{1}{2}(\partial_0\phi)^2 - \frac{v_\phi^2}{2}|\nabla\phi|^2 - \frac{1}{g_s^2}\text{Tr}[\varepsilon\mathbf{E}^2 - \frac{1}{\lambda}\mathbf{B}^2].\end{aligned}\quad (3)$$

where the gluon strength is

$$F_{\mu\nu} = \partial_\mu g_\nu - \partial_\nu g_\mu - [g_\mu, g_\nu] \quad (4)$$

and

$$E_i = F_{0i}, \quad B_i = \frac{1}{2}\varepsilon_{ijk}F_{jk}. \quad (5)$$

The parameters  $\varepsilon$  and  $\lambda$  are the dielectric constant and the magnetic permeability of the dense condensed medium. In the CFL vacuum the gluons  $g_0^a$  and  $g_i^a$  acquire Debye and Meissner masses given by

$$m_D^2 = \alpha_T g_s^2 F_T^2, \quad m_M^2 = \alpha_S g_s^2 F_S^2 = \alpha_S g_s^2 v^2 F_T^2. \quad (6)$$

where

$$v^2 = \frac{F_S^2}{F_T^2}. \quad (7)$$

It should be stressed that these are not the true rest masses of the gluons, since there is a large wave function renormalization effect making the gluon masses of the order of the gap  $\Delta$ , rather than  $\mu$  [27]. One can decouple the gluons solving their classical equations of motion neglecting the kinetic term. The result from Eq. (3) is

$$g_\mu = -\frac{1}{2}\left(X\partial_\mu X^\dagger + Y\partial_\mu Y^\dagger\right). \quad (8)$$

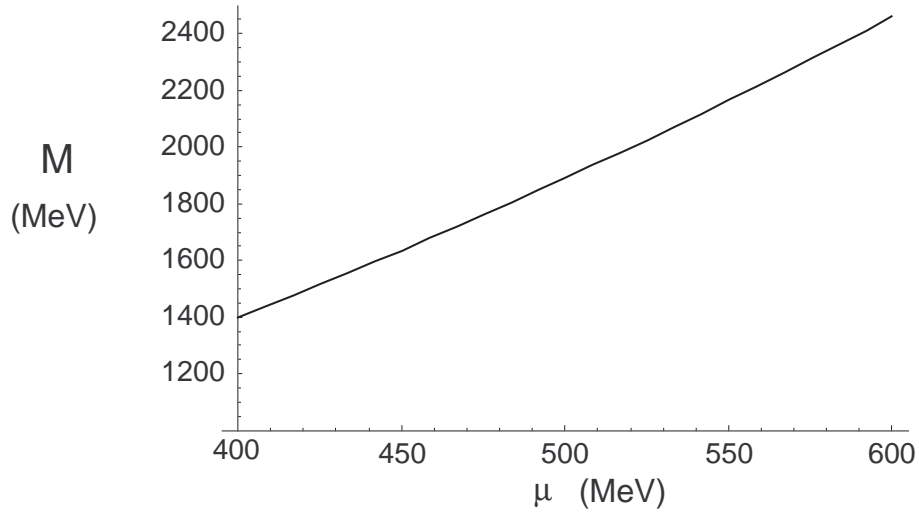
By substituting this expression in Eq. (3), and performing a gauge rotation to get  $Y = 1$ , one gets

$$\mathcal{L} = \frac{F_T^2}{4}\left(\text{Tr}[\dot{\Sigma}\dot{\Sigma}^\dagger] - v^2\text{Tr}[\vec{\nabla}\Sigma \cdot \vec{\nabla}\Sigma^\dagger]\right) + \frac{1}{2}\left(\dot{\phi}^2 - v_\phi^2|\vec{\nabla}\phi|^2\right) - \frac{1}{g_s^2}\text{Tr}[\varepsilon\mathbf{E}^2 - \frac{1}{\lambda}\mathbf{B}^2]. \quad (9)$$

with

$$E_i = \frac{1}{4}[\Sigma\partial_0\Sigma^\dagger, \Sigma\partial_i\Sigma^\dagger], \quad B_i = \frac{1}{8}\epsilon_{ijk}[\Sigma\partial_j\Sigma^\dagger, \Sigma\partial_k\Sigma^\dagger]. \quad (10)$$

Apart for the breaking of the Lorentz symmetry, one recognizes in the first term the chiral lagrangian and, in the last one, the Skyrme term [19]. This effective lagrangian enforces the idea of the quark-hadron continuity between the CFL and the hypernuclear matter phase with three flavors. A numerical estimate of the soliton mass based on these assumptions is in Fig. 1 (for  $\Delta = 40$  MeV).



**FIGURE 1.** The soliton mass  $M$  at finite density in the CFL phase as a function of the baryonic chemical potential  $\mu$ , for the value of the gap  $\Delta = 40$  MeV.

Around 400 MeV the soliton mass is in the range of 1200-1400 MeV, which, in the light of the quark-hadron-continuity, is in the right ball-park. If pentaquarks exist at zero density, they should be connected continuously with states comprising two diquarks and an antiquark existing at finite density.

Spectroscopy and the study of the hadron structure may appear as old-fashioned sectors of hadron physics. They are however from time to time also source of surprises in theoretical physics. We have discussed the recent excitement about pentaquarks. Another much debated subject a decade ago concerned the proton spin. On this subject U. D'Alesio gave a talk on the role of the intrinsic partonic  $k_T$ . The dependence on intrinsic partonic  $k_T$  in parton distribution function (pdf) can be parameterized by a gaussian shape and is born by a twist 2 operator (Sivers) whose effect on asymmetries is competitive with another source of asymmetry, the so called Collins effect. Its presence in the pdf is of interest in single spin asymmetries for inclusive production by high energy transversely polarized hadron hadron scattering. D'Alesio and collaborators [28, 29] give predictions for several transverse single spin asymmetries, e.g. at RHIC. In particular single spin asymmetries in Drell Yan processes can provide a tool to extract quark Sivers distribution functions, while the inclusive production of  $D$  by high energy transversely polarized hadron hadron scattering could be a tool to extract gluon distribution

function. Related to this study is another talk given in Section E, by I. Vukotic for the HERA-B Collaboration, who presented results for charmonium and open charm production obtained by this collaboration. In particular a new limit

$$\sigma(D^0 \rightarrow \mu^+ \mu^-) = 2.0 \times 10^{-6} \quad (90\%CL) \quad (11)$$

was presented, currently the best published upper limit for this decay.

## NEW PHYSICS EFFECTS

The discussion on soliton states at finite density in the CFL is a useful reminder that actually we do not yet know the true ground state of QCD at intermediate densities, i.e. those corresponding to quark chemical potentials  $\mu \sim 400$  MeV. It is possible that the QCD ground state is characterized, at these densities, by inhomogeneous color superconductivity. This state is called LOFF state [30], [31], [32]. Its prominent feature is diquark condensation with non vanishing total momentum of the Cooper pair, so that  $\Delta = \Delta(\mathbf{r})$ . The dynamics of these phases was investigated by P. Castorina in the framework of non-commutative field theories (NCFT) with cut-off [33, 34].

The hypothesis that space coordinates do not commute:

$$[x_\mu, x_\nu] = \Theta_{\mu\nu} , \quad (12)$$

can be traced back to Snyder [35]. The condition (12) can be realized in quantized motions of particles in strong magnetic field  $H$  and the non commuting coordinates can be appropriately chosen on a plane perpendicular to  $H$ . Castorina gave a talk on this subject with an overview on NCFT. Several cases of NCFT have been studied so far. They are based on the use of the Moyal product of fields:

$$(f \star g)(x) = \exp \left\{ i \frac{\Theta_{\alpha\beta}}{2} \partial_\alpha \partial'_\beta \right\} f(x) g(x')_{x=x'} \quad (13)$$

that implements non commutativity by means of the parameters  $\Theta_{\alpha\beta}$ . Castorina and collaborators study transitions from ordered phases with homogeneous order parameters to phases with inhomogeneous order parameters. NCFT with cutoff  $\Lambda$  are used as an effective approach to describe the dynamical mechanism underlying these transitions. They consider two applications, one for  $\lambda \phi^4$ , in the context of Bose-Einstein Condensation, and another one for Nambu Jona Lasinio four-fermion coupling, that can be used either in the context of superconductivity or for spontaneous breaking of chiral symmetry. In the latter case one considers:

$$\mathcal{L} = i\bar{\psi}\gamma \cdot \partial \psi + g\bar{\psi}_\alpha \star \psi_\alpha \star \bar{\psi}_\beta \psi_\beta - g\bar{\psi}_\alpha \star \bar{\psi}_\beta \psi_\alpha \star \psi_\beta . \quad (14)$$

For  $g$  larger than a critical value  $g_c$  one has chiral symmetry breaking to a phase with inhomogeneous order parameter. The space modulation of the gap is similar to the LOFF case with a Cooper pair momentum  $P \propto 1/\Theta\Lambda^2$ .

C. Corianò and A. Feo gave talks on supersymmetric models. In the analysis of spectra and hadron multiplicities for collisions induced by Ultra High Energy Cosmic

Rays (UHECR) it is important to model the effects of new physics, to get a quantitative understanding of their role in experimental observables. Corianò presented results on the modifications induced by SUSY models not only on UHECR but also in deep inelastic scattering. The simulations he presented [36, 37] include effects due to low energy gravity scales induced by extra dimensions. Numerical effects can be significant indeed, and might manifest themselves in new generation experiments, be they collider physics experiments or cosmic rays observations.

Feo presented a study of dynamical breaking of supersymmetry by non perturbative lattice techniques, using the hamiltonian formalism in a class of  $d = 2, N = 1$  Wess Zumino models [38, 39] (see also [40]). Their study includes an analysis of the phase diagram by analytical strong coupling expansions and numerical simulations. All results with cubic prepotential indicate unbroken SUSY, while for quadratic potential

$$V = \lambda_2 \phi^2 + \lambda_0 \quad (15)$$

they confirm the existence of two phases. At high  $\lambda_0$  there is a phase characterized by broken SUSY with unbroken  $Z_2$ . At low  $\lambda_0$  SUSY is unbroken and  $Z_2$  is broken. The critical value of  $\lambda_0$  they find is

$$\lambda_0^c = -0.48 \pm 0.01 . \quad (16)$$

## CONFINEMENT IN YANG-MILLS AND SUPER YANG-MILLS

The last two talks I wish to summarize were presented in Section E by K. Konishi and A. Niemi. They have in common the study of topological effects in the discussion of confinement in Yang Mills theories. As is well known, the simplest gauge model with monopole solution is the Georgi-Glashow model, based on the group  $G = SU(2)$  and containing a triplet of Higgs fields:

$$\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}(D\phi)^2 + \lambda(\phi^2 - v^2)^2 \quad (17)$$

where

$$D_\mu \phi^a = \partial_\mu \phi^a + g \epsilon_{abc} A_\mu^b \phi^c . \quad (18)$$

After symmetry breaking a symmetry subgroup (e.m.) remains:  $H = U(1)_{e.m.}$ . The model has soliton solutions with charges

$$q = 0, \quad g_M = \frac{1}{g} \neq 0 . \quad (19)$$

The model can be generalized to other groups  $G, H$  usually in the small  $\lambda$  limit (Bogomol'snyi, Prasad, Sommerfield). It is a simplified model but full of interest. Among the other things, it teaches us that microscopic variables in the lagrangian (e.g. in  $\mathcal{L}$  the fields  $\phi, A$ ) do not necessarily coincide with observed quanta, that are massive gauge bosons and monopoles. In QCD similar differences arise between microscopic (quarks, gluons) and macroscopic (hadrons) degree of freedoms. Which ideas on confinement

arise from this analogy? A popular vision of confinement is based on the idea that two color charges at large distances  $R$  form a flux tube, i.e. a string like, one-dimensional object with an energy  $V(R) \sim \sigma R$ . Confinement might be explained by analogy with type II superconductors. Let us consider two magnetic monopoles. Since magnetic flux is conserved and cannot vanish everywhere, it remains confined to vortex lines (Abrikosov vortices) characterized by

$$E/R \simeq \sigma = \text{const.} \quad (20)$$

Now in QCD one needs chromoelectric, not chromomagnetic flux tubes, i.e. one needs Cooper condensation of pairs of magnetic charges (dual Meissner effect). In normal QCD magnetic monopoles do not exist as particles, but in supersymmetric QCD (SQCD) they can exist, as first shown by Seiberg and Witten.

Konishi discussed several models [41, 42] of monopole confinement by vortices. After the construction of nonabelian BPS vortices he proves that nonabelian monopoles occur as infrared degree of freedom (e.g. in  $N = 2, SU(N_c)$  SQCD). This suggests that softly broken  $N = 2$  theories might model QCD confinement. The existence of nonabelian monopoles in these models is essentially a quantum mechanical phenomenon. A peculiar feature of these models is that massless flavor symmetry is important to keep  $H$  unbroken and for being part of the dual transformation itself.

Niemi discussed a model with glueballs as closed strings [43]. These topological solutions are stabilized by the existence of twists or knots. Their stability follows from topological considerations, e.g. the existence of twist or knots of the closed string. The model is based on the Yang-Mills theory with two colors. In the infrared regime one separates  $A_\mu$  in a  $U(1)$  e.m. component  $A_\mu$  and charged  $A_\mu^\pm$ . By these components a composite gauge field  $\Gamma_\mu$  can be constructed for an internal group  $U(1)_\Gamma$ . The model can be casted in a form similar to a dual superconductor with 2 condensates (as in metallic hydrogen or high  $T_c$  superconductors). The vortex lines have a two-sheet structure which allows for twisting and knots. Stability of the closed strings follows from this non trivial topological structure.

These two talks have shown once again that topological solitons (vortex lines) constitute a lively subject of study. Therefore a deeper understanding of the topological structure of QCD, or some SUSY extension of QCD, can shed light on the dynamics of color confinement, perhaps rendering this *millennium problem* (see the site <http://www.claymath.org/millennium>) eventually solvable.

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